The DART cylindrical, infrared, 1 meter membrane reflector

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ABSTRACT

The Dual Anamorphic Reflector Telescope (DART) is an architecture for large aperture space telescopes that enables the use of membranes. A membrane can be readily shaped in one direction of curvature using a combination of boundary control and tensioning, yielding a cylindrical reflector. Two cylindrical reflectors (orthogonal and confocal) comprise the 'primary mirror' of the telescope system. The aperture is completely unobstructed and ideal for infrared and high contrast observations.

The DART high precision testbed researches fabrication, assembly, adjustment and characterization of $\tilde{1}$ meter cylindrical membrane reflectors made of copper foil or kapton. We have implemented two metrology instruments: a non-contacting, scanning profilometer and an infrared interferometer. The profilometer is a laser confocal displacement measuring unit on an XYZ scanning stage. The infrared interferometer uses a cylindrical null lens that tests a subaperture of the membrane at center of curvature. Current surface figure achieved is 25 μm rms over a 50 cm diameter aperture.

Keywords: anamorphic, cylindrical reflector, membrane optics, space telescopes, metrology

1. INTRODUCTION

The current generation of telescopes, both ground and space based, can trace their design and fabrication methods back to the telescopes of the 17th century. There is no a priori reason that a space telescope should look anything like a ground based one. In the space environment the mechanical elements of the telescope are in free fall and hence do not feel the effects of gravity, so constraints imposed by gravity are nonexistent. Nor is there any reason that the traditional methods of fabrication, essentially the rubbing of two pieces of glass together with some abrasive grit in between, should be used to figure the optical surfaces used in a telescope. The overriding consideration is that the telescope be large, lowmass, and diffraction limited over a reasonable field of view. For applications in the infrared, the telescope needs to be cooled to cryogenic temperatures to reduce the thermal emission from the reflector surfaces.

The DART Dual Anamorphic Reflector Telescope is a system of two cylindrical-parabolic reflectors. One reflector produces a line focus; two reflectors, properly oriented, produce a point focus. This system is ideally suited to using tensioned membranes for the reflective elements, and hence a lowmass telescope system. For farIR/submillimeter missions the DART presents a compelling new telescope architecture that is scalable to large apertures.

Membranes are exceedingly difficult to shape in 2 directions of curvature, but a membrane can be more readily shaped in one direction of curvature using a combination of boundary control and tensioning. This yields a cylindrical reflector. A cylinder produces a line focus. A second, perpendicular cylinder produces a spot focus. The cylindrical reflectors are also parabolic to eliminate spherical aberration. To make the telescope unobstructed, the first cylinder is a segment of an off-axis parabola. The 'primary mirror' of the telescope system is comprised of two cylindrical reflectors. In order to form a point focus, the focal lengths of the two reflectors must be unequal. Hence, the system is anamorphic.

a precision testbed was constructed for the purposes of exploring and quantifying the fundamental accuracy limits of the DART system. The goal is a terrestrial testbed capable of diffraction-limited imaging at mid-infrared wavelengths and to discover the fundamental difficulties to creating such a system.

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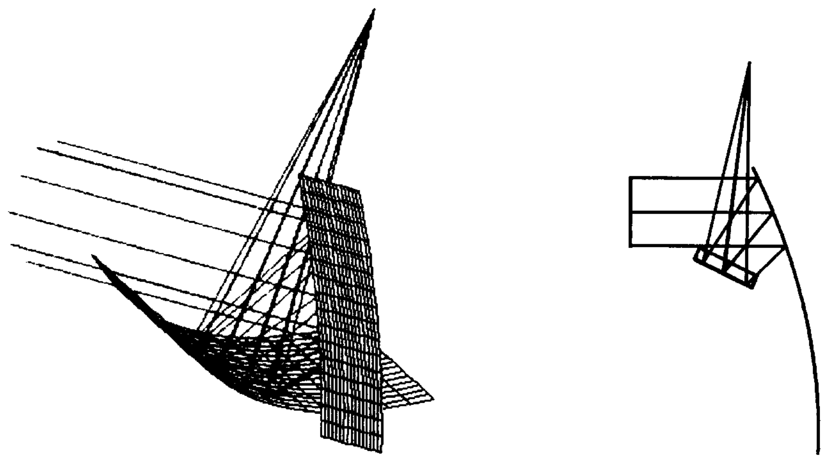


Figure 1. The layout of the DART two mirror reflector system of parabolic cylinders. The edge on view on the right illustrates the decentration of the off-axis segment from the parent parabola.

2. SINGLE REFLECTOR TESTBED HARDWARE

The tesbed researches fabrication, handling, assembly, shaping, control and characterization of cylindrical membrane reflectors. The testbed encompasses the design of the membrane tensioning and control hardware and the development of the metrology instruments. The membranes are 70 cm by 80 cm and made of copper foil, though other materials are readily substituted. The membrane figure goal is less than 2 μm rms with a surface measurement accuracy of 0.15 μm rms.

The initial precision testbed examines a single membrane. The DART architecture is comprised of two cylindrical membranes, one of which is a segment of an off-axis parabola and the other of which is a shorter focal length and has the curvature profile of an on-axis membrane. Due to its axial symmetry, the on-axis membrane is more straight forward to implement and was chosen for the single reflector testbed. The emphasis of this effort is on precision - demonstrating, developing the necessary technology, understanding and technique to produce a surface accuracy of nearly 1 μm over a 1 meter membrane. This will be a unique accomplishment, as other efforts have shown a 40 μm rms figure for a 1.2 m cylindrical membrane(LM),[1] and 39 μm rms for ROC = 3.04 m, dia = 33 cm ([2] and 100 nm rms ROC = 32 m, dia = 10 cm .[3]

2.1. Membrane Frame Design

In the single reflector testbed design, the reflector is formed by stretching a membrane in one direction to provide stiffness and enforcing the curvature in the perpendicular direction through a combination of shaped edge clamps and precisely-shaped rails which lightly push into the stretched membrane. Clamping bars along two opposing edges hold the membrane in tension while the other two edges are free. The tension forces are reacted through the edge clamp bars into a preload frame. The preload frame also serves as a mounting fixture for the precision shaping rails and as an interface to the mirror support and alignment systems. A diagram of the current design is shown in Figure 2. Note the alignment mechanisms at each clamp bar that adjust the membrane preload and boundary displacements. The alignment and shaping adjustability is a key feature of this testbed design. The baseline membrane is 50 micron metal foil and measures 80cm by 70cm rectangular, but other membranes can be subsitituted readily. The modularity of the design is purposeful; it is expected that the membrane shaping hardware will be modified and improved before the full telescope testbed is constructed.

2.2. Membrane Installation

Membrane installation involves preparing and installing a membrane into the tensioning frame. Membranes wrinkle easily when handled, so a handling procedure was developed. Once in the frame, the membrane is not

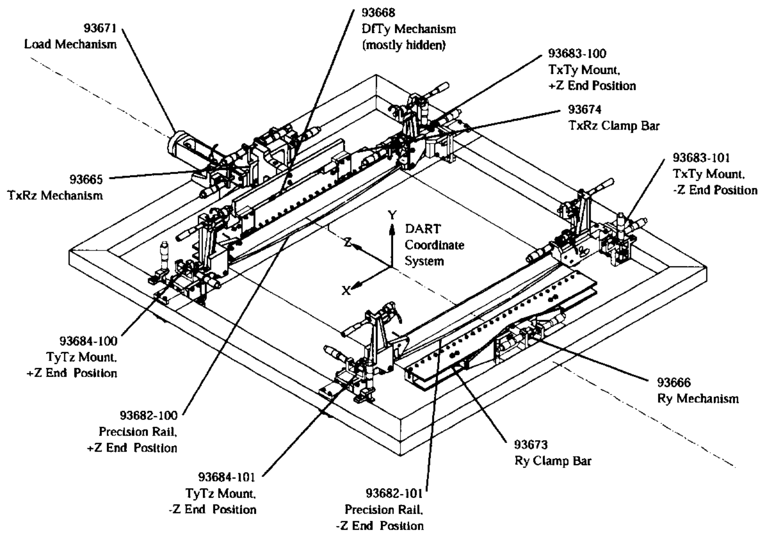


Figure 2. Mechanical layout of a single reflector mounting frame, showing the parabolic clamping bars, the alignment mechanisms and the precision shaping rails.

directly handled. The frame is handled as an assembly and placed in front of the metrology instruments. Next the clamp bars are aligned. Then the precision rails are mounted on the frame and aligned.

For membrane installation, we developed an installation jig. The jig supports the membrane in a curvature matching the clamp bars and holds the clamp bars in alignment while the membrane is secured. The jig provides repeatability for the placement of the clamp bars with respect to the tensioning frame.

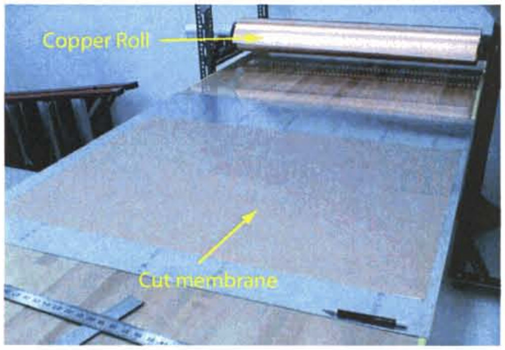
2.3. Initial Adjustment

The initial adjustment of the membrane is accomplished using templates, plastic shims and visual observation. The initial adjustment is normally performed with 20 lb. of force on the upper clamp. The upper clamp assembly weighs about 10 pounds, so the tension on the membrane is approximately 10 pounds. When the reflector frame is picked up off of the installation jig the micrometers that position the clamp jaws are snubbed. This stabilizes the membrane while it is being transferred to the optical table and sets the starting point for the adjustments. Aluminum templates machined to the same curve as the clamp jaws are used to check the curve of the membrane. The templates are set on blocks near the mounting location for the precision rails. Plastic shim stock is used to measure the irregularities in n the membrane shape.

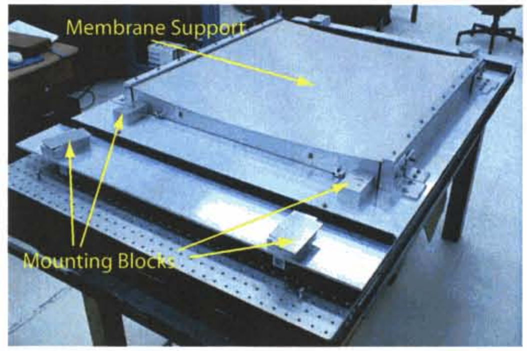
The critical adjustments are the rotation of the lower clamp about Y and the rotation of the upper and lower clamps about X. Rotation of the lower clamp about Z is also adjusted. The adjustments are performed with micrometers.

When the membrane shape is acceptable it is scanned. After the initial scan the force on the upper clamp is increased to 30 pounds and the membrane is scanned again. Then the force is increased to 40 pounds, our final tension and the membrane is scanned again. Another iteration of adjustments and scans is performed.

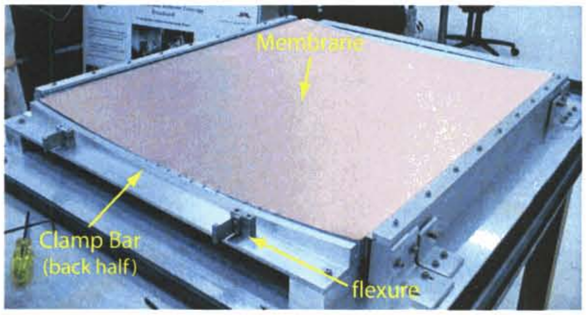
The precision rails are installed now. The precision rails are mounted on the frame, but not in contact with the membrane. The precision rails are driven forward using four micrometers until there is contact at the outside edges of the membrane. The four micrometers are then driven forward equally in small steps until the precision rails are in contact across the full width of the membrane. The contact is checked with a .0005 thick plastic shim. When contact across the membrane is accomplished the membrane is scanned. Further adjustment of these four micrometers may be required in order to achieve the best RMS for the membrane. Each adjustment is followed by a scan until it is determined that the best shape has been achieved.



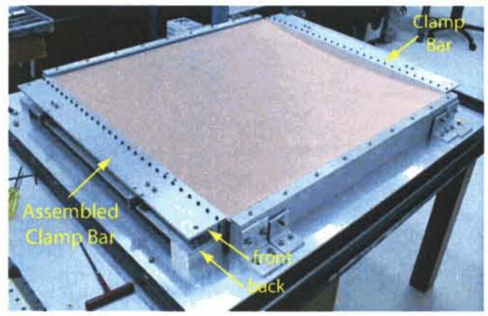
(a) The membrane is cut and slid onto a thin sheet of aluminum and set aside.



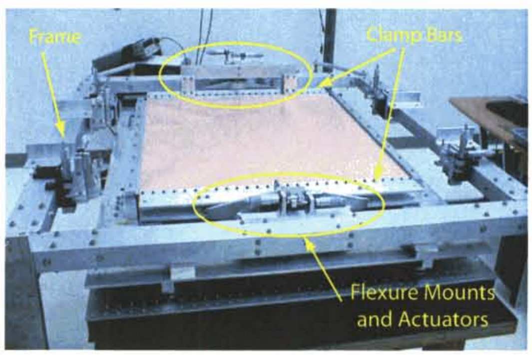
(b) The installation jig just before placement of the clamp bars. The jig supports the membrane during installation.



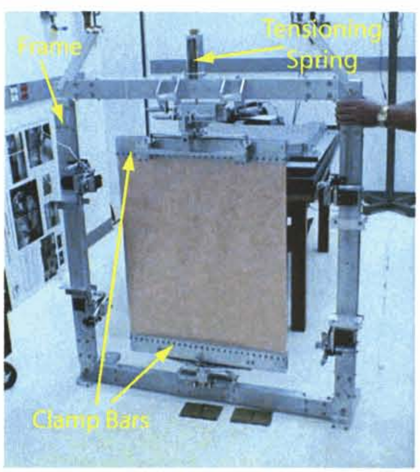
(c) The back halves of the clamps are attached to the installation jig and checked for alignment. The membrane is transferred to the jig.



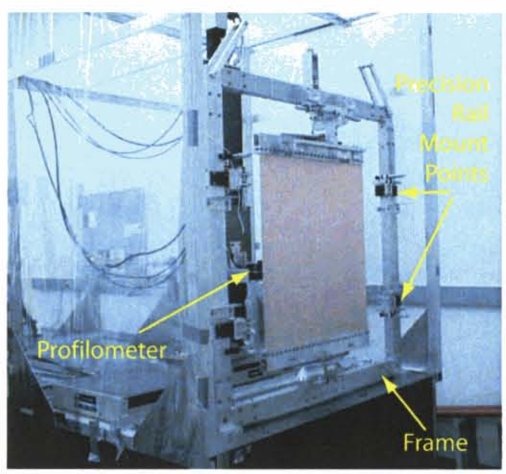
(d) The clamp halves are bolted together with 6-32 bolts at 20 inch/ounce of Torque from the center out.



(e) The tensioning frame is carried to the installation jig, aligned to the clamps, and attached.



(f) The assymbly is raised $\frac{1}{8}$" off the jig and the membrane tensioned to 20 lbs. The assembly is set upright.



(g) The reflector assembly is lifted on to the table in front of the profilometer.

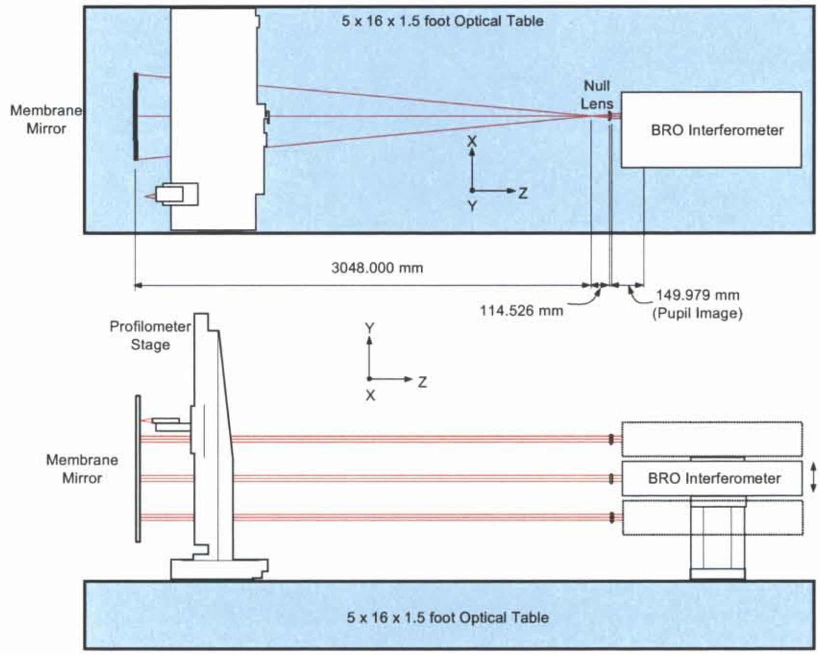


Figure 4. The reflector, profilometer and interferometer sit on the same optical table. During interferometric measurements, the profilometer stage is moved to the edge of its range, leaving the membrane unobstructed.

3. METROLOGY SYSTEMS

Measuring the surface of a one-meter cylindrical membrane presents a particular challenge. The metrology must be noncontacting, produce minimal vibration, and service a large aperture of cylindrical shape. Additionally, the metrology tools are needed to measure the membrane as it undergoes the shaping and adjustment process. This places a requirement of a very high dynamic range and ease of alignment on the system.

The optical metrology systems encompass a suite of tools with a tiered approach. The metrology tools are an interactive component of membrane shaping and are also used for precision characterization of the final shape. Qualitative techniques assist with coarse shaping. Quantitative instruments inform finer shaping.

The coarsest shaping is performed by mechanical templates as part of the initial adjustment described in the previous section. At this stage, the membrane is examined optically with center of curvature imaging. This shows the entire membrane and is especially useful for showing wrinkles and other large scale features. It is only qualitative. Next we use the profilometer to refine the membrane shape. The highest precision measurements are provided by the interferometer.

We have implemented two quantitative metrology instruments: a non-contacting, scanning profilometer and an infrared interferometer. The profilometer is a laser confocal displacement measuring unit on an XYZ scanning stage. The noise is under 2 μm rms with repeatability limited to 10 microns. The performance of the profilometer has been characterized in the environment, on a calibration flat, and on a 1 meter cylindrical membrane. The infrared interferometer uses a cylindrical null lens that allows a subaperture of the membrane to be viewed. It has a dynamic range of 320 μm and acquires data quickly, freezing environmental effects.

3.1. Center of Curvature Imaging

Center of Curvature imaging reveals the entire membrane. The images show qualitative and dramatic results of overall membrane smoothness and large scale ripples. It is a verification of the coarse shape. It is useful for diagnosing repeated features in the copper material and systematic errors created by the tensioning frame.

Center of Curvature imaging is traditionally used on rotationally symmetric optics with a knife edge (Foucault test) or a grating (Ronchi test). For a source placed at the center of curvature of a sphere, all light rays return

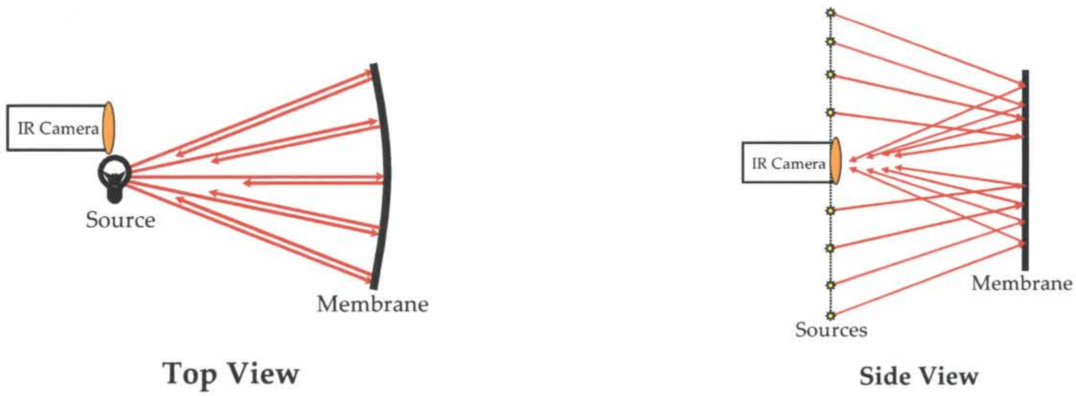


Figure 5. In the Top View of cylindrical membrane under center of curvature test, all rays from a point source return to the source. In the Side View, the membrane acts as a flat mirror.

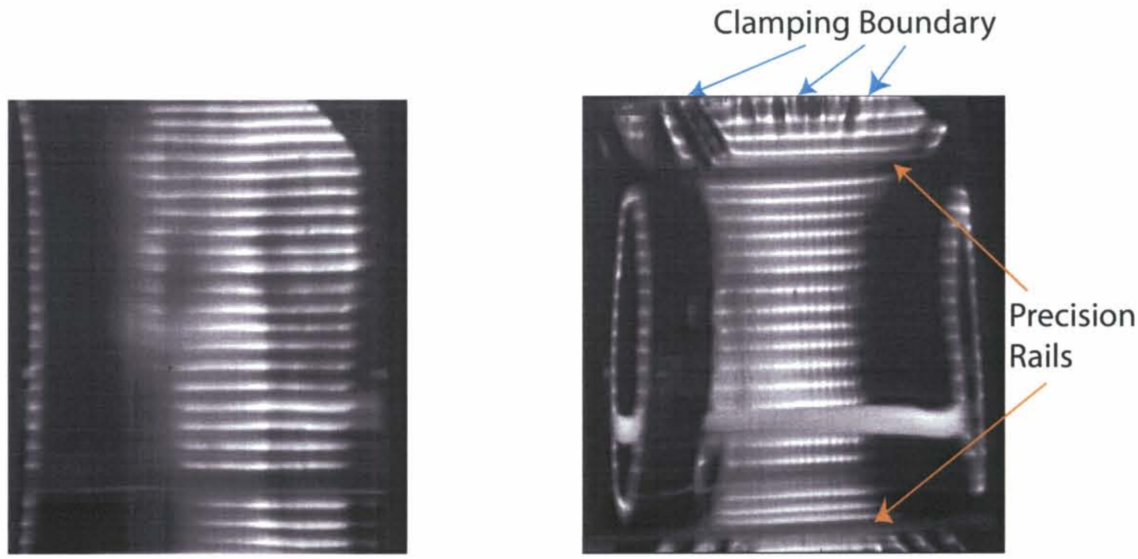


Figure 6. An infrared image of a vertical series of point sources positioned at the center of curvature of a cylindrical membrane. The left membrane is made of 5 mil thick Kapton and shows good alignment of the clamp bars. The right membrane is copper with precision rails. The precision rails smooth the membrane and push ripples to the outer edge.

on themselves. To an observer also at center of curvature, the point source will appear as uniform illumination across the surface of a perfectly spherical mirror. For a perfectly spherical cylinder, a point source appears as a uniform line. A string of sources (parallel to the cylindrical axis) produces a ladder of lines, as illustrated in Figure 5. Gaps or breaks in the line indicate a different radius of curvature or a different local slope.

Figure 6 shows images of the cylindrical membrane taken at center of curvature. The sources are light bulbs 1 inch size mounted on a 5 foot long pole. The image is taken with an infrared camera, a microbolometer array identical to the camera in the interferometer. Both membranes are seen to be very smooth over a large central area. Outside the useable aperture at the left and right edges, the membrane curves up. The images show smoothness for a good alignment of the clamp bars. When the precision rails are added, the ripples in the membrane migrate to the zone between the rails and the clamp bars, leaving the central aperture smooth.

3.2. Profilometer

The profilometer measures the surface height of the membrane as it situated vertically on the optical table, as shown in Figure 7. The profilometer is capable of scanning one square meter of area with a surface height range of 5 cm. It is composed of a laser head mounted on a fine resolution z-translation stage mounted on a large, 1-meter of travel XY stage. It has an accuracy of under 2 μm, as detailed in Appendix ??.

The Laser head measures surface height by the active confocal principle. It is made by Keyence, model LT-8110 and has a 0.2 μm precision with a 2 mm range. To increase the range, the laser head is mounted on an Aerotech, computer controlled Z translation stage with 5 cm range. The z-stage and the laser head are operated in a closed loop mode in order to follow the shape of the surface under measurement. The z-stage is moved until the laser head reads zero surface height. This allows for arbitrary shapes to be measured and does not require *a priori* knowledge of the surface profile. This is particularly important for shaping the precision rails and for characterizing the clamp bar shapes.

The X translation stage is an Aerotech linear motor with 1 meter of range. The Y stage is an Aerotech vertical linear ball screw motor with 1 meter of range that rides on top of the X stage. The XY stage has a resolution of 100 nm and maximum slew rate of 1 meter per minute. Due to vibrations caused by the stage, measurements cannot be made while the stage is scanning. The stage must stop and settle for at least 0.1 second before taking a surface height measurement. This causes the membrane scans to be time consuming. A high resolution scan with measurements on a 5 mm grid requires 6 hours. We typically use a faster three line scan with 1 cm samples in the x direction and 18 cm separation in the y direction of the lines. This scan takes 15 minutes and is used for refining the membrane shape. The majority of the results presented use this scan.

The triple-line scan data is fit to a parabolic cylindrical surface. The radius of curvature and the rms error from the fit is reported. The main figure of merit on membrane quality is the rms error from the best fit cylinder. Several other features are used for diagnostic analysis of the membrane. The triple-line scan data is broken into individual lines and fit to individual parabolas. The skew of the top to the bottom are compared to show any misalignment of the top and bottom clamp bars and/or precision rails. The fit error on the top/bottom sections are compared to the center section to determine propagation of tension across the membrane. The copper material repeatedly exhibited poorer figure in the middle line scan while the Kapton exhibited poorer performance on the outer edges.

A series of standard triple scan runs were taken to tune two operating parameters: the feed rate and the dwell time. The mean displacement measurement was of course zero since the feedback was in operation. The mean deviation of the displacement measurement determines how well the system performs. There were 363 points in each data sample. Plotted in Figure 9 are the results of this study. They show that the resolution of the displacement measurement is at the 1 μm level provided you have a dwell time greater than or equal to 0.5 second and a feedrate of 200 mm/minute or slower. Sources of noise (mechanical, electronic) in the current system prevent doing any better.

The profilometer performance was tested on a optical flat. The flat was 10 inches in diameter and had a known flatness of 63 nm. The flat was scanned with the Y stage in continuous 14 cm passes in the positive and negative Y direction. The measured surface height had a standard deviation of 2.1 μm. The scans in the X direction exhibited 18 μm of thermal drift and are being repeated.

Based on these measurements, the accuracy of the surface height measurement is concluded to be limited to just under 2 μm by the XY stage. This is currently exceeds the membrane figure. When the membrane figure is closer its goal, the interferometer will be necessary to make the figure measurement to the required accuracy.

3.3. Interferometer

While the profilometer is capable of scanning the entire membrane surface within the precision rails, such a scan is slow and has a repeatability uncertainty of 10 μm. Interferometry provides make a faster, near instantaneous measurement and a higher precision. The data acquisition is performed in 0.25 seconds, (longer for averaged measurements), so most of the environmental vibration effects on the membrane are frozen. The vibrations not frozen can be averaged out over repeated measurements.These fast measurement facilitate in the repeated measurements required for model validation and influence function characterization.The copper material used

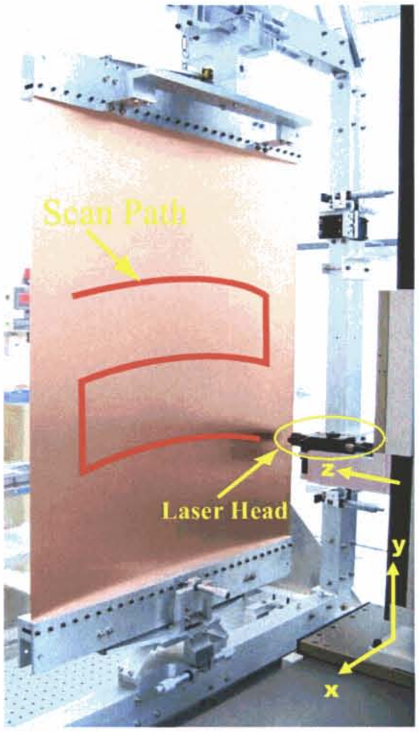


Figure 7. The profilometer laser head is mounted on an XYZ translation stage. The stage allows for full scanning coverage of the membrane.

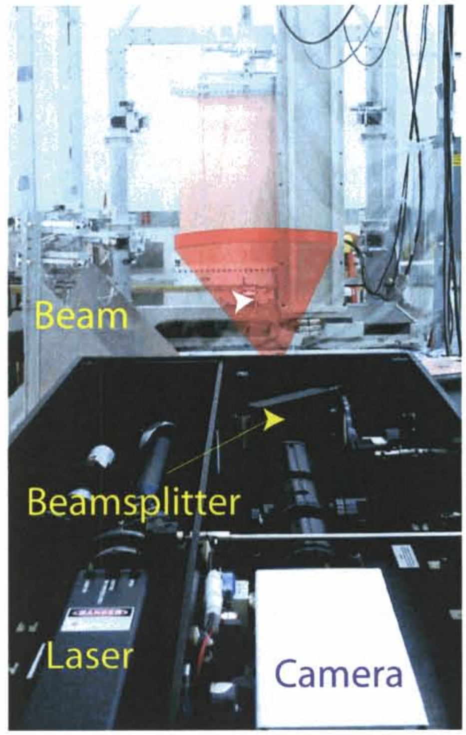


Figure 8. Photograph of infrared interferometer placed at center of curvature of the membrane. A small null lens produces a testbeam that is 30 mm tall and 80 cm wide.

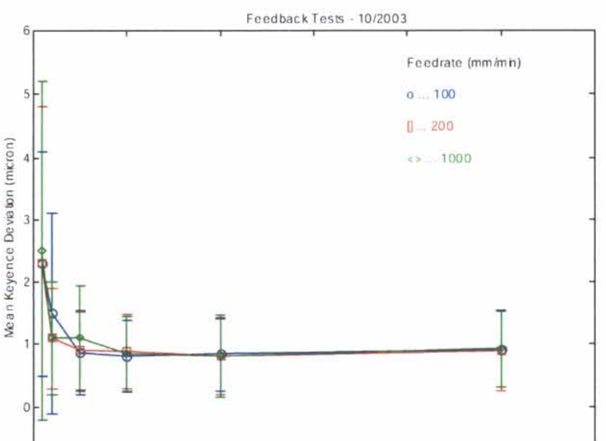


Figure 9. The resolution of the displacement measurement is $\tilde{1}$ μm provided the dwell time is greater than or equal to 0.5 second and the feedrate is 200 mm/minute or slower.

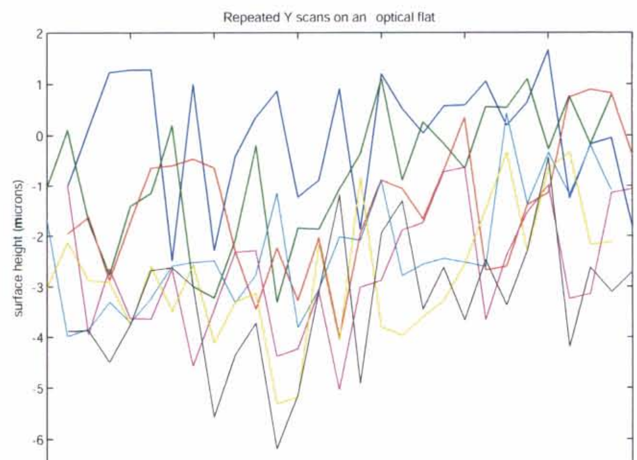


Figure 10. An optical flat was scanned repeatedly in X and in Y.

Table 1. Surface error of membranes made of 70 μm thick copper, 35 μm thick copper, and 5 mil thick Kapton. The listed figure of merit is the rms deviation from a best fit parabolic cylindrical surface.

Membrane	No Precision-Rail		Precision-Rail	
	50 cm scan	60 cm scan	50 cm scan	60 cm scan
70 micron copper 62.5 cm wide November 2003	.0679 mm	.1632 mm	.0604 mm	.1261 mm
35 micron copper 62.5 cm wide February 2004	.1230 mm		.0700 mm	
70 micron copper 70 cm wide September 2003		.205 mm		.103 mm .0902 mm
5 mil. Kapton	.0389 mm			
70 cm wide	.0441 mm	.0503 mm		
March 2004	.0502 mm		.0513 mm	
			.0437 mm	.0631 mm
			.0351 mm	.0514 mm
			.0279 mm	.0438 mm

in the membrane is diffuse at visible wavelengths but smooth in the infrared. Consequently, the interferometer must use an infrared laser and detector.

In the interferometry setup, the single reflector is tested at center of curvature. A small ZnSe null lens produces a cylindrical reference beam that matches the ideal parabolic cylindrical surface. The reference beam measures a subaperture of the cylindrical membrane that is 80 cm wide by 30 mm high. The spatial sampling is 4 mm wide by 120 μm high.

The infrared interferometer is a heritage instrument manufactured in 1985 by BRO. It is a phase shifting, infrared interferometer with a 30 mm diameter collimated output. It uses a 1.5 W CO_2 laser at 10.6 μm wavelength. The detector is a 320x240 microbolometer array with standard video output. The phase shifting is performed by a computer controlled PZT on the internal reference mirror. The BRO interferometer has a measured precision of 0.13 μm and dynamic range of 340 mm.

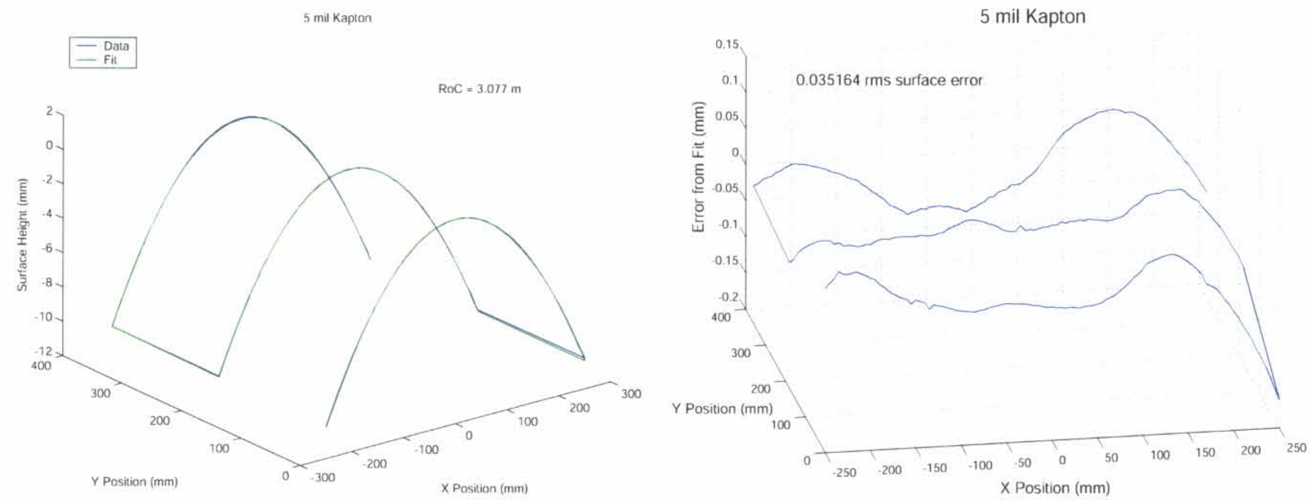
4. RESULTS

We have performed over twenty membrane installations and adjustments. We have developed procedures for installation and adjustment that optimize the membrane figure. The best membrane figures are listed in Table 1. This table represents membranes made of electroformed Copper 70 μm thick, 35 μm thick, and 5 mil thick, aluminized Kapton. The 5 mil Kapton membrane is under 25 lbs of tension, the copper membranes are all at forty lbs. The current results suggest that the precision can improve the radius of curvature but do not improve RMS.

The best figure was achieved with Kapton, 35 μm rms. An exemplary data plot from a profilometer measurement of the Kapton membrane is shown in Figure 11. A higher resolution scan is shown in Figure 12. The rms deviation from a best fit parabolic cylinder is 36.6 μm over the 60 cm rectangulare aperture and is dominated by edge roll off. The figure improves for decreasing circular apertures: 25.7 μm rms for 40 cm diameter, 18.3 μm rms for 30 cm diameter, and 10.8 μm rms for a 20 cm diameter aperture.

4.1. Precision Rail Characterization and effect

The precision rails were shaped while measuring them with the profilometer. The ideal shape was a parabola with Radius of Curvature of 3.048 m. The lower rail deviated by 24 μm rms and the upper rail deviated by 36 μm rms.



(a) Surface Scan (b) Residual to best fit parabola

Figure 11. Profilometer scan of the membrane surface height fitted to a parabolic cylinder. The best fit radius of curvature is 3.077 m. The error from the best fit parabolic cylinder is 35 μm rms.

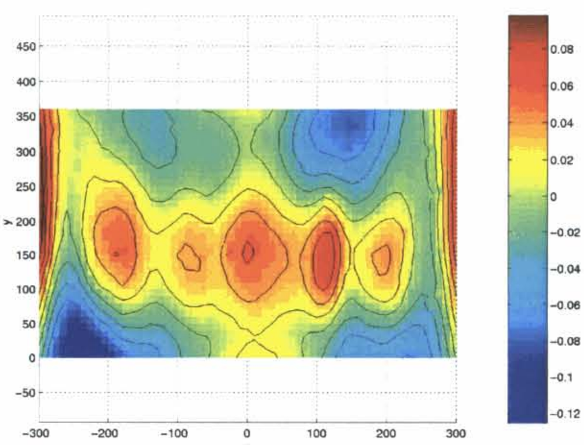


Figure 12. High resolution profilometer scan of the Kapton Membrane under 40 lbs of tension. Plotted is the error from a best fit parabolic cylinder.

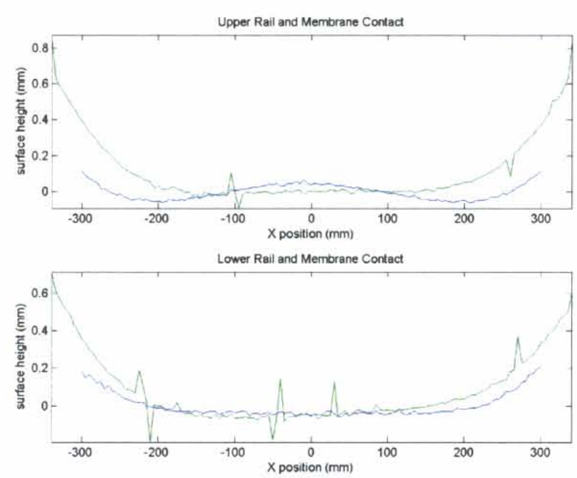


Figure 13. The precision rails contact the front surface of the membrane. At the contact height, the back surface of the membrane was measured by the profilometer. The deviation from the ideal parabola of Radius of Curvature 3048 mm is plotted. Expected roll off at the edges is seen.

Table 2. The curved surface of the clamp bars was measured with the profilometer. Each curve was fit in least-squares fashion to a sphere. The measured radius of curvature and rms deviation from a best sphere is listed. The radii of curvature match to within 0.8%. The surface error is close to the repeatability limit of the profilometer.

measurement	best fit sphere R_C (mm)	rms fit error (μm)
lower front	3053	16
lower back	3037	14
upper front	3044	13
upper back	3025	10
upper membrane	3037	10

Once the rails are mounted, the true shape of the membrane is determined by the depth to which the rails is pushed into the membrane. The membrane shape was determined by measuring the membrane on the side opposite of the precision rails. The membrane follows the shape of the rails rather well, except for expected deviations near the outer edges, as seen in Figure 13.

4.2. Clamp Bar Characterization

The clamp bars are machined with a spherical profile. The target profile for the membrane is parabolic, however the difference between a parabola and a sphere with 120 inch radius of curvature is 2.5 mils P-V, which is about the standard machine precision available. The true parabolic shape will be produced by the precision rails.

The clamp bars were scanned using the profilometer to characterize the accuracy of the curves and to determine any deformation present when the two halves are clamped together. The curved surface of the clamp bars was measured with the profilometer as seen in Figure 4.2. Each curve was fit in least-squares fashion to a sphere. The best fit radii were found to be within 0.8% of the target. The rms deviations from a sphere were also small, averaging 13 μm. Near the clamp bar, the membrane follows the shape of the clamp. The radius of curvature is between the radii measured for the front and back clamps.

The distortion due to clamping the front and back bars together was determined by measuring the flat, outsides of the bars. The flat sides of the upper and lower front and back halves were measured separately. Then the front and back halves were clamped together at the normal 20 pounds of torque, with a narrow strip of membrane to act as a spacer. After clamping, the flat sides were remeasured. A small amount of distortion was present when the two halves are clamped together - 0.1 mm of curvature. The effect of the distortion on the curved surface was calculated. The distortion measured on the flat side was subtracted from the inner curve for each of the 4 clamp halves. The distortion is the same direction and magnitude for the top and the bottom. Consequently, the global error contributed to the membrane is low order, only a change in the radius of curvature, not the surface regularity.

The clamp bars after inspection are considered to be within specifications and not a source of error for the membrane figure. The alignment of the clamp bars and the tension points on the clamp bars are still under investigation.

4.3. Alignment and Repeatability Testing

To determine the repeatability of the membrane installation and alignment procedure, three membranes were installed with the identical process. The membranes were made of 70 μm thick copper, 70 cm wide. The membranes were cut from the roll of copper with the same orientation to the curvature. The membranes were scanned over a 60 cm wide aperture with the profilometer. The measured surfaces were fit to a parabolic cylindrical surface with a Radius of Curvature of 3.04 m. The errors from the ideal parabolic cylinder were 100, 119, and 108 μm rms with precision rails. These results show that surface figure is repeatable to under 9%.

ACKNOWLEDGMENTS

This work was funded by NASA Code R and performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

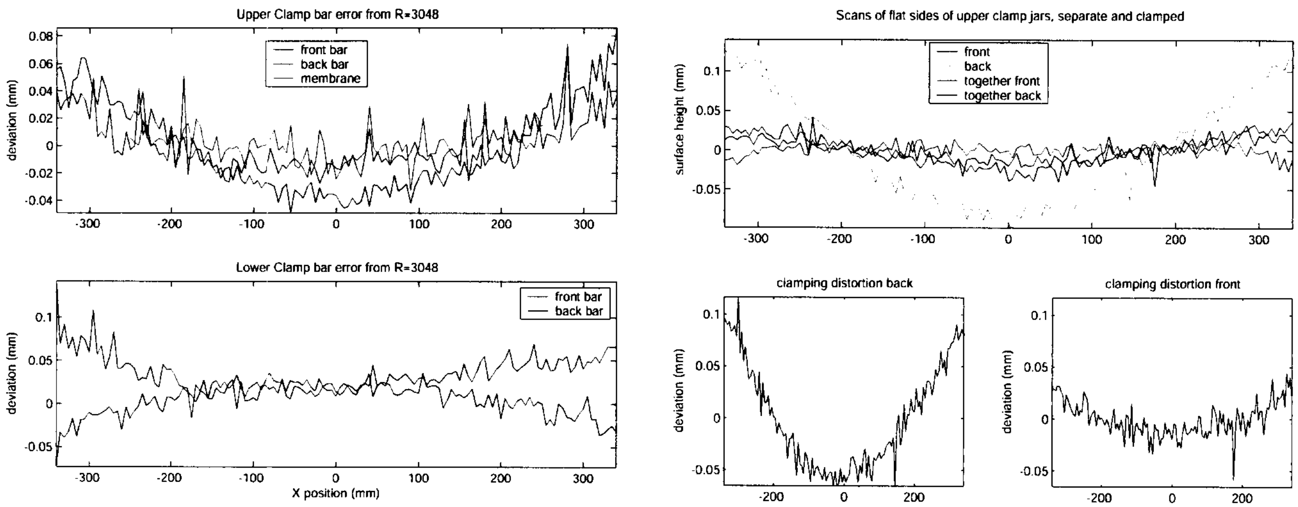


Figure 14. The inner, curved surfaces of the clamp bars were measured with the profilometer. The deviation from the ideal sphere of Radius of Curvature 3048 mm is plotted (left). The outside, flat surface of the clamp bars was also measured. The flat surface is distorted by $\tilde{0}.1$ mm P-V by clamping the bars together.

Table 3. Three membranes were installed with the identical process and measured with the profilometer. The surface data was fitted to a parabolic cylinder with Radius of Curvature of 3.04 m. Listed is the error from the fit with and without precision rails.

	rms fit error (μm)	
membrane	No Precision-Rail	Precision-Rail
first	158.0	100.0
second	208.0	118.8
third	157.4	107.6

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